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Challenges in meeting all of India's electricity from solar: An energetic approach

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ABSTRACT

India's electricity requirements will continue to grow with its increasing population and urbanization. Climate change, increased carbon emissions, and the depletion of nonrenewable energy resources have forced India to shift to renewable energy resources. India's solar potential is large enough to provide 100-percent of its current electricity requirements if photovoltaic arrays and energy storage infrastructure of sufficient size is deployed. In this paper, we modeled the dynamics of net electricity input and output from a photovoltaic electricity (PV) system as it is built out to provide the entire electricity demand by 2050. The results showed that building a PV system large enough to meet the nation's entire electricity demand by 2050 is possible; however, it will require a rapid increase in the deployment of solar PV and the associated storage infrastructure over the next few decades. Such rapid expansion of the PV system will require substantial electricity allocation away from general societal use and towards building the photovoltaic system equipment and integrating it with existing infrastructure. This will lead to a short-term lack of electricity supply for general use by society.

1. Introduction

1.1. Background

The Indian government is pushing for the adoption of renewable energy technologies to reduce the carbon emissions from electricity generation. Under the Paris Agreement, India committed to having at least 40% of its total installed capacity from renewable resources by 2030 [1]. Subsequently, the share of electricity from renewable resources is projected to increase from 15% in 2016 to 24%, and the carbon intensity of generating a single unit of electricity is expected to be reduced by 29% by 2026–2027 [2]. However, under the existing policy scenario, India's carbon emissions from the electricity sector will only be reduced on a per kWh basis rather than in absolute terms, as shown in Fig. 1. The carbon intensity of electricity generation is expected to decrease from 0.732 kg CO2/kWh in 2015-16 to 0.522 CO2/kWh by 2026-27; however, the total emissions will increase to 1113 million tons from 810 million tons during the same period.

However, more ambitious policy objectives must be adopted to reduce carbon emissions. Limiting the global temperature rise to between 1.5–2 °C will require significant cuts in global carbon emissions by 2050 IPCC, [3,4]. As India is the third-largest carbon emitter [5] and electricity generation accounts for almost 40% of its total carbon emissions [6], decarbonizing electricity generation will be crucial to global climate change mitigation.

1.2. Renewable electricity potential in India

India has vast potential for renewable energy generation, particularly from solar resources. A substantial amount of decarbonization of India's electricity sector must come from electricity derived from solar resources. While India's potential for renewable resources, such as wind, is considerable, it is insufficient to meet the country's electricity demand. India's maximum wind potential is estimated to be 300 GW [7] and wind turbine capacity factors range from 0.13 to 0.19 in states with high wind potential [8]. Assuming an average capacity factor of 0.16, the maximum electricity that can be generated from 300 GW of wind resources will be less than 15% of the projected electricity demand in 2050 [9]. However, India has vast potential for solar resources. Barren and non-arable land accounts for 5% of India's total area, equal to 170,000 km 2 [10]. Assuming that it requires five acres of land to install 1 MW of solar PV [Central Electricity Regulatory Commission (CERC),

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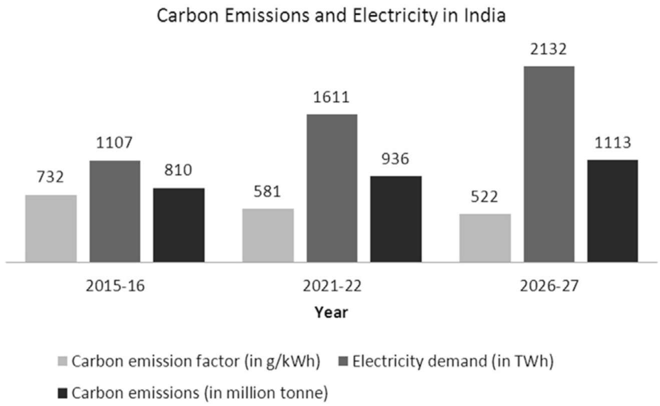

Fig. 1. Current and projected carbon emissions from electricity generation in India [2].

[11]], theoretically, 8500 GW of group-mounted solar PV can be installed using only the barren land. Solar PV can also be complemented with 352 GW of rooftop PV [12]. By using economically and commercially viable solar energy technologies [13,14], India's entire present and future electricity demand can be met through solar PV, as shown in Table 1.

1.3. An overview of challenges in rapid deployment of solar in India

Several authors have reviewed challenges in deployment of solar technology on large scale in India. Moallemi et al. reviewed the historical transitions on the development of on-grid solar and concluded that there is a need for favorable government interventions and political support for meeting 100 GW solar PV target by 2022 [15]. Hairat and Ghosh evaluated techno-economic challenges of adding 100 GW solar power in India by 2022 [18]. Goel indicated that a lack of consumer awareness, effective net-meter policies, skilled-workforce, and innovative business models will make it difficult to meet the policy goal of 40 GW of rooftop solar PV by 2022 [19]. NITI Aayog, a government policy think-tank in India, and Manju and Sagar highlighted higher financial and investment risks and lack of expertise in financial institutions for funding renewable energy projects make it commercially risky to start large scale renewable energy projects in developing countries such as India [7,20]. NITI Aayog also pointed out that lack of demand due to unwillingness of utilities to purchase renewable electricity from generators may slow down rapid deployment of renewable energy including solar PV [7]. In addition to these soft challenges, several reports argue that without the expansion and upgrading of India's transmission and distribution grid, the pace of integration of solar PV is likely to be limited size by the existing grid [19,21]. The temporal scope of these studies was limited to 2022 and these studies focused on overall deployment capacity of 100 GW, far smaller than what is required for decarbonization of the grid.

Decarbonization of electricity sector by 2050 will require deployment of clean energy technologies on a terawatt scale [22–24], which will likely pose additional challenges. These challenges include lack of political-will to transform electricity system [25], high investment costs of solar PV and lack of storage technologies [20], which may make electricity unaffordable, poor grid reliability due to increased share of renewables [26], and possibly shortage of certain materials [27,28].

1.4. Energetic challenge in rapid deployment of solar

Some researchers have pointed out that most challenges discussed in literature ignore physical constraints to terawatt scale deployment of renewable energy technologies and have examined the challenges associated with a large-scale deployment of solar, along with other renewables, through an energetic lens [24,29]. Energetic analyses model energy inputs and outputs through an energy system over the energy system's entire lifespan. A viable energy system should be able to deliver more energy than the energy required in its manufacturing and maintenance over its lifetime [30–32]. If an energy system is a net energy sink, the energy system cannot be a source of energy for society because the system itself requires more energy from external sources than it can provide. Thus, energetic analyses are more insightful for understanding the challenges in transitioning to a different energy system because these approaches use information in physical units [33,34].

Through this type of energy lens, solar energy systems are energetically viable; i.e. these systems generate more energy than the energy required for manufacturing and maintaining them over their useful lifetime. However, a significant portion of the system's energy investment in manufacturing them is front-loaded [35–37] causing the PV system to only become net energy positive in the later part of its life cycle. Depending upon the deployment rate, a national scale solar energy system may require substantial external energy allocation to support its expansion during the initial years before the energy system becomes a net energy surplus [38]. These points have been raised in earlier studies, and the phenomenon is called 'energy cannibalism' [29,39–41].

Furthermore, the inherent intermittency of renewable resources makes the large-scale integration of solar into the grid difficult [42]. However, building long and geographically dispersed transmission lines [43], designing an appropriate mix of solar and wind [44], and energy storage [45,46] can potentially overcome technical challenges to certain extent. Moreover, simulation results show that energy storage is absolutely necessary for electricity generation exclusively from intermittent renewable technologies [45]. Thus, the deployment of solar large enough to meet entire electricity demand must be supplemented by a large-scale deployment of storage technologies.

Energy storage technology will also require energy investment and further decrease the solar energy system's net energy surplus [47,48]. Under a rapid-growth scenario, such external energetic support would create short-term energy scarcity for society, making decarbonizing politically and socially challenging. Studies have focused on energetics to assess the feasibility of low-carbon energy technologies; however, to the best of the author's knowledge, no study has quantified the implications energy cannibalism of transitioning to a low-carbon energy system which integrates energy storage. This paper quantifies these

Table 1
Solar PV-based electricity potential in India.

Technology	Electricity demand (TWh)[a]	Capacity factor	Required PV capacity to meet electricity demand (in GW)[c]	Available capacity (in GW)[d]
Electricity demand in 2015–16	1100	0.18[b]	700	8850
Projected electricity demand in 2050	4000		2540	

[a] Based on information and projections in [2,9].
[b] There is enormous geographical diversity in distribution of the solar potential in India [15,16]; Average values were assumed to be representative of all India. The capacity factor was found to vary between 0.16 and 0.20 for most locations in India [17], and it was assumed to be equal to the average (0.18) for this study.
[c] Demand/(capacity factor*8760).
[d] Total 8500 GW ground-based PV on barren land and 350 GW rooftop PV.

energetic implications in the Indian scenario using data and concepts from the existing literature.

1.5. Objective of the study

The purpose of this paper is to highlight potential socioeconomic and environmental challenges and tradeoffs in meeting India's electricity demand exclusively from renewable resources by 2050. The specific objective is to quantify the energetic implications of the large-scale deployment of renewable resources in India. The scope of this study is limited to solar resources and PV technology, as it is likely to play a dominant role in decarbonizing India's electricity sector.

1.6. Contribution of study

The contribution of the study is twofold. First, earlier studies focusing on similar analysis (e.g. [38]) exclude role of storage from energetic analysis, which could significantly affect energy flows. Second, this study focuses on energy transformation in a developing country. The challenges of generating one's entire electricity demand from renewables are likely to be different in India for two reasons. One reason is India's electricity demand, which is growing, and it is expected to triple by 2050 [9,49]. Renewable electricity will be needed not only to provide additional demand but also to substitute for the existing supply. Another reason is limited availability of wind resources, due to which solar resources will have to supply an overwhelmingly large portion of the electricity demand, which may increase the size of energy storage infrastructure needed for grid stability.

2. Methodology and data

2.1. System description

A graphical representation of the electricity input and output from a PV system is shown in Fig. 2. A PV system generates only electricity, and the system itself will consume some portion of the electricity to support its growth and maintenance. The remaining fraction will be available for societal use. If the system's growth rate is high, it is possible that even the entire output from the PV system will be insufficient and that the system will require electricity from external sources, likely from existing power plants, to support its growth.

The energetic analysis in this paper differs from previous analyses. Earlier studies have carried out energetic analyses by converting the inputs and outputs of different energy types (electricity, heat, and transport fuel) into a single equivalent unit [47,50,51]. However, there are extremely limited viable renewable energy alternatives for the industrial process heat and freight transport sectors [52,53]. In addition, the electrification of process heat and freight transport seems to be a distant dream due to technical constraints [54,55]. Thus, this paper considered only electricity inputs and outputs.

2.2. Net electricity flow model

The mathematical representation of net electricity from a PV system is described using Eqs. (1)–(3). Annual gross electricity produced (AEP) from the electricity system was calculated using Eq. (1). Annual energy invested (AEI) in the electricity system for its growth and maintenance was calculated using Eq. (2); AEI is the sum of electricity invested for adding new PV and storage capacity in any given year. Net electricity output (NEO) from a PV system at any year ‘t’ is the difference of AEP and AEI.

$$AEP_t = 8760^* \sum_{i \in I} CF_t {}^* TPV_t \tag{1}$$

AEP_t = Annual gross annual electricity production
TPV_t = Total capacity of PV in year ‘t’
CF_t = Capacity factor in year ‘t’

$$AEI_t = \sum_{i \in I} EE_{PV} {}^* NPA_{it} + \sum_{j \in J} EE_S {}^* NSA_t \tag{2}$$

AEI_t = Annual electricity investment in electricity system
NPA_t = New PV added in year ‘t’
NSA_t = New storage added in year ‘t’
EE_{PV} = Embodied electricity in PV system
EE_S = Embodied electricity in storage

$$NEO_t = AEP_t - AEI_t \tag{3}$$

Eqs. (4) and (5) calculate the annual installed capacity and the retired capacity of PV in year ‘t’. ‘RC^{PV}’ is the retired capacity of PV, which needs to be replaced with additional new capacity, and it is equal to PV capacity added lifetime ‘L^{PV}’ years ago.

$$NPA_t = TPV_t - TPV_{t-1} + RC_t^{PV} \tag{4}$$

$$RC_t^{PV} = NCA_{t-L^{PV}} \tag{5}$$

L^{PV} = Lifetime of PV system

Eq. (6) calculates the annual storage capacity added in year ‘t’. ‘$RC^{storage}$’ is the retired storage capacity, which needs to be replaced with additional new capacity, and it is equal to the ‘NSA’ added lifetime of storage ‘$L^{storage}$’ years ago. ‘TS_t’ is the storage system's total capacity in year ‘t’ (for more details on calculating storage capacity, see Eq. (10) in Section 2.3.2). The lifetime of the PV and storage was assumed to be 30

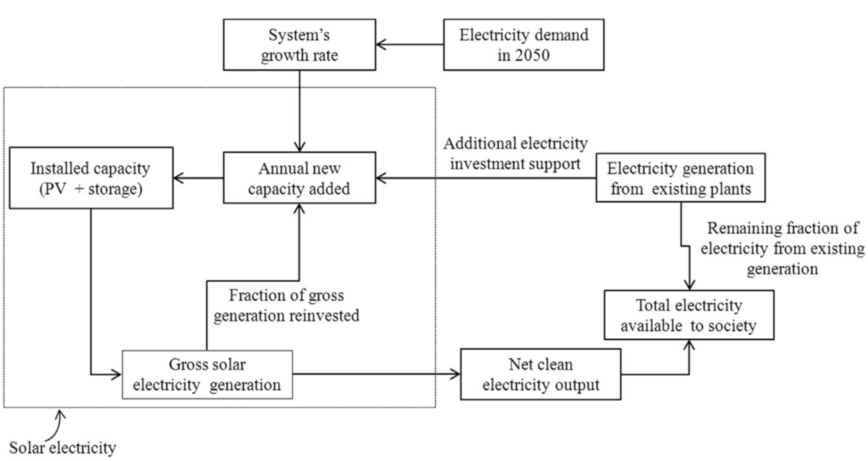

Fig. 2. Electricity input and output of a PV electricity system.

years [56].

$$NSA_t = TS_t - TS_{t-1} + RC_t^{storage}(in GWh) \quad (6)$$

$$RC_t^{storage} = NSA_{t-L^{storage}}(in GWh) \quad (7)$$

$L^{storage}$ = Lifetime of storage

2.3. Data for the model

2.3.1. Growth rate of PV system

A logistic curve (sigmoid function or S-shaped curve) was used to model the growth trajectory of the total (cumulative) PV installed capacity. The logistic growth curve has been used to show several stages of the overall growth trajectory of a technology's diffusion [57–60]. The curve's initial stage shows a slow diffusion rate or adoption rate, followed by rapid exponential growth, and eventual growth saturation as deployment asymptotically approaches some final upper limit. Our growth model, represented by Eq. (8), is based on the population growth model developed by Pierre François Verhulst in 1838 [60,61].

$$TPV_t(in GW) = \frac{Upper limit}{1+e^{-k*(t-t_m)}} \quad (8)$$

In this model, ‘k’ represents the curve's steepness, ‘tm’ represents the mid-point inflection point, and ‘upper limit’ is the maximum capacity that needs to be installed. Table 2 shows the values of the different parameters.

The values for parameters (k and t_m) were chosen to correlate the existing government targets as accurately as possible, as shown in Fig. 3. The Indian government aims to achieve 100 GW of solar PV capacity by 2022, up from 8–10 GW of capacity in 2016 [7]. However, the government has not finalized any specific targets beyond 2022 [62].

This study's upper limit was 2600 GW, which represents the total installed PV capacity required to meet the total electricity demand in 2050. This upper limit was calculated based on the total electricity demand in 2050 and the PV capacity factor of 0.18. India's electricity demand projections between 2016 and 2050 are shown in Fig. 4. These projections are based on a growth rate of 3.8%, which is the average of the various growth rates (i.e., 2.5% and 4.9%) available in the existing literature [9,63].

2.3.2. Storage size

Storage is one solution to reduce the demand for backup capacity and to develop a 100-percent renewable electricity system while maintaining grid stability and ensuring reliable electricity supply when the sun is not shining [44,46,64,65]. Storage units will store excess electricity and then release electricity back into the grid during non-producing periods. The need for storage to address the intermittency concerns of solar energy resources lowers the EROI of solar PV and the net energy available for societal use [47].

Calculating the storage capacity necessary for electricity system running only on solar PV100 is difficult. In general, storage capacity depends on two variables, as shown in Eq. (9) [47,56,66,67]. ‘S’ is the total storage capacity, ‘P’ is the storage system's rated power capacity (in GW), and ‘h’ is the required number of storage hours.

$$Storage\ capacity(in\ GWh) = P*h \quad (9)$$

There are extremely limited estimates available for the ‘P’ and ‘h’

Table 2
Assumed parameters Solar PV growth model.

Solar PV logistic growth parameters		
Steepness of growth (k)	**Half-target year (t_m)**	**Upper limit (GW)**
0.4	2030	2600

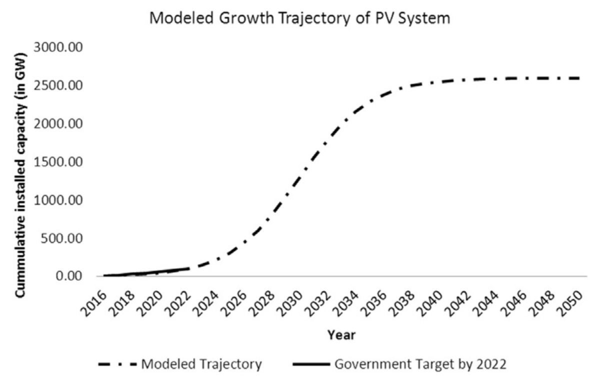

Fig. 3. Modeled growth trajectory of total installed capacity of PV.

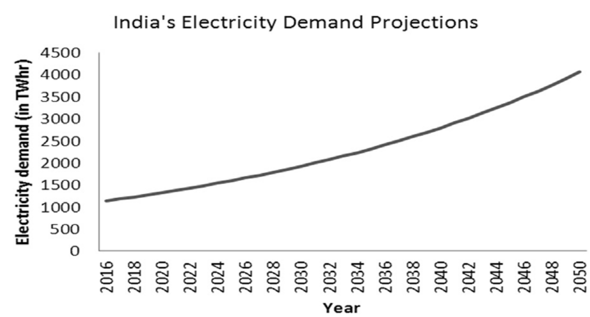

Fig. 4. India's electricity demand projections (assuming the electricity demand was equal to 1142 TWhr in 2016 [2], which then grows 3.8% annually until 2050).

values of a system running on 100-percent variable renewable electricity. Steinke et al. [65] and MacKay [67] suggested that for designing storage to support a 100-percent renewable electricity system, the ‘P’ value can be assumed to be equal to the average power demand. MacKay [67] indicated that ‘h’ needs to be up to 120 h (five days) to cope with short-term fluctuations in the renewable energy supply, such as a lull in wind speed. Weißbach et al. [47] assumed a storage time of 10 days to address the intermittency issues of a PV and wind electricity system in Germany.

In this study, it was assumed that the required capacity rate of storage ‘P’ in any year ‘t’ is equal to the total installed capacity of solar PV in India in that year. The storage capacity was calculated using Eq. (9) and is shown in Eq. (10) by multiplying the total number of hours in ‘d’ days.

$$S_t = TIC_t*d*24\ \ (in\ \ GWh) \quad (10)$$

2.3.3. Embodied electricity

Table 3 shows the embodied electricity of solar PV; 65% of the gross embodied energy in a solar PV plant is electricity [47]. The embodied electricity of PV was derived after multiplying 0.65 with the embodied energy values reported in [33]. One reason for the huge variations in embodied energy values is the individual studies’ assumptions and boundary conditions [36]. For both the PV and the storage system, the range's average value was assumed to be the representative value for the calculations.

Table 4 shows range of embodied energy required to construct unit capacity of electricity storage. As only aggregate values of embodied energy intensity were reported in literature [56,69], it was assumed that 50% of the embodied energy was electricity.

2.4. Uncertainty analysis

The values of a few important variables may significantly influence the PV system's net electricity supply. These variables are the PV's

Table 3
Embodied energy and electricity of Solar PV.

	Range of embodied energy intensity (MWh/MW) (A)[a]	Share of electricity (in percentage)[b] (B)	Range of embodied electricity intensity (MWh/MW) (A*B)	Value used this study (MWh/MW) (average of min. and max value in column three)
Solar PV	1000–15000	65%	65–9750	4908

Note: Although all values are reported in electrical energy unit equivalent, the values in the third and fourth columns represent actual electricity consumption.
[a] Based on the range given in [33,68].
[b] Based on the percentage value reported in [47].

embodied electricity intensity and the storage technology and storage size. Using the range values shown in Tables 3 and 4, input variables were used to account for uncertainties, as shown in Table 5.

3. Results

The overall model described in Eqs. (1)–(10) was run for various scenarios developed using different combinations of the input values shown in Table 5. For each scenario, the left axis in the following figures shows the output trajectories of gross electricity generated from the PV system, the embodied electricity in PV and storage, the net electricity supply from the PV system, and the electricity demand. The right axis shows the percentage of demand met from the PV system.

3.1. Scenario I

In this scenario, the 'low' set values from Table 5 were used, which indicate that the PV system has small electricity investment intensity for its development and maintenance, and the storage requirement worth is only a single day. From the output trajectories shown in Fig. 5, the PV system's rapid growth between the mid-2020s to the late 2030s requires a minor effect on the net electricity output, and the PV system can meet society's entire electricity demand by the 2030s; in fact, the PV system's net output overshoots the demand by 50% until the demand catches up with the supply by 2050. This represents the best-case scenario, as all input values are low.

3.2. Scenario II and Scenario III

Medium embodied electricity values with a storage requirement of one day and low embodied electricity values with a storage requirement of 10 days were used in scenario II and scenario III, respectively. The results in both scenarios are similar, as shown in Figs. 6 and 7. The net electricity output becomes negative for five to six years during the rapid growth years between 2025 and 2030. Thus, the PV system will require electricity from external sources to grow at such a rapid pace. In fact, the requirement is equal to almost 30% of the electricity demand, which implies that society must invest up to 30% of its electricity consumption into the PV system to support its growth. However, the PV system gradually grows and becomes a net electricity supplier for the remaining period, from 2034-35 to 2050.

Table 5
Scenarios and corresponding values of input variables.

Range of values	Embodied electricity intensity of PV (in TWh/GW)	Embodied electricity intensity of storage (in TWh/TWh)	Size of storage (in number of days)
Low	0.065	37	1
Medium	4.905	192	7
High	4.905	192	10

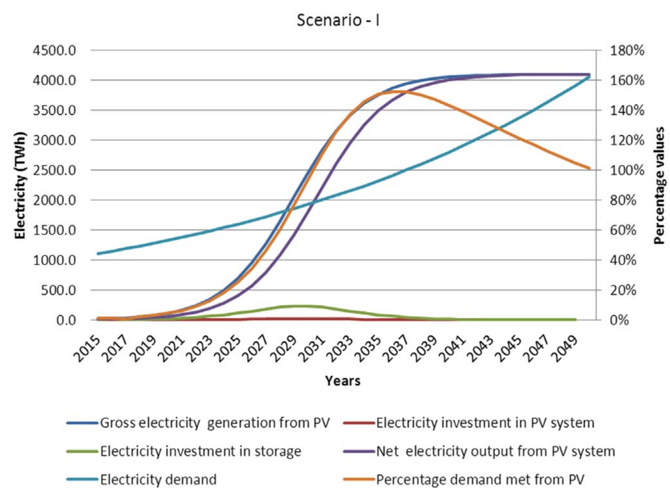

Fig. 5. Energetic flows in scenario I.

3.3. Scenario IV

In this scenario, average intensity values with a storage requirement for 10 days were used for the analysis. The results are shown in Fig. 8. The PV system's rapid growth requires enormous electricity from external sources. In fact, the deficit reaches more than five times the societal consumption (electricity demand) during 2029–2030; therefore, to support the PV system's planned growth, society must invest five to six times the electricity it consumes for a few years. Thus, in this scenario, it is impossible to build the PV system for the given intensity values and a storage requirement of 10 days.

Table 4
Embodied energy for unit capacity of electricity storage.

	Range of embodied energy intensity (MWh/MWh) (A)	Share of electricity in embodied energy (in percentage)[b] (B)	Range of embodied electricity (MWh/MWh) (A*B)	Value used this study (MWh/MWh) (average of min. and max value in column three)
Storage technology	73–694[a]	50%	37–347	192

Note: Although all values are reported in electrical energy unit equivalent, the values in the third and fourth columns represent actual electricity consumption.
[a] For different storage technologies reported in [56].
[b] Our own assumption; other values (0–100%) are tested in sensitivity analysis.

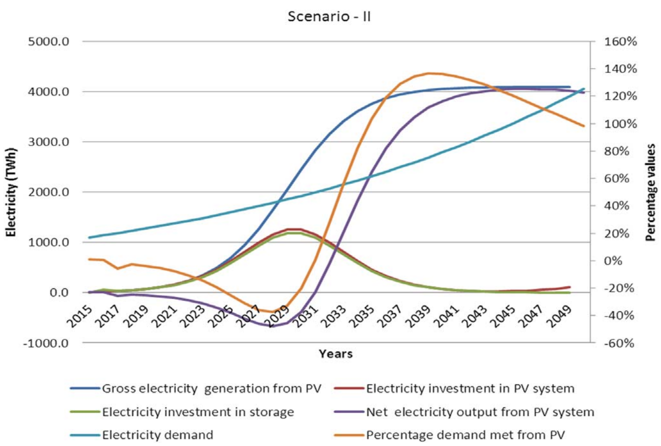

Fig. 6. Energetic flows in scenario II.

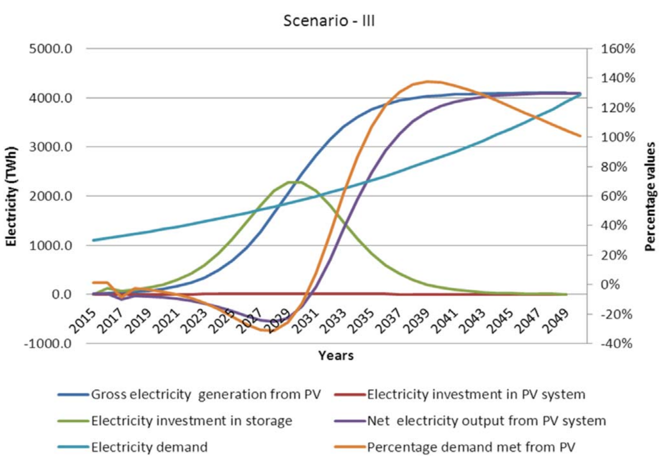

Fig. 7. Energetic flows in scenario III.

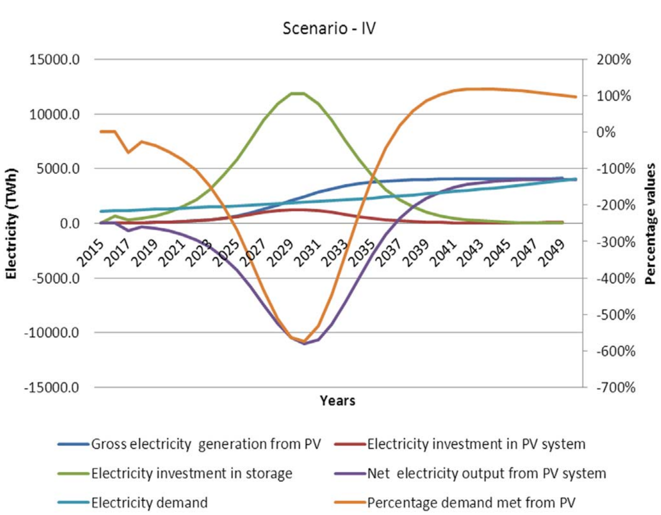

Fig. 8. Energetic flows in scenario IV.

4. Discussion

As the world shifts toward a low-carbon electricity infrastructure, such as a PV system, more and more energy investment will be required during the initial years to build the system. The current global PV capacity became a net energy positive [50,70]; thus, the whole installed solar PV capacity now generates more electricity than the total energy invested to manufacture the PV system itself. Furthermore, the existing PV system provides an extremely small share of electricity globally, and a much higher PV installation rate will be required for meaningful decarbonization by 2050 [71].

Jacobson and Delucchi [22,72] suggested an ambitious path to a sustainable energy future by 2030 in the U.S. and worldwide; however, achieving a similar target in India will require rapid deployment of solar PV. A PV system has much lower net energy output than conventional fossil fuel-based generation [47]. Thus, supporting the rapid deployment, as well as the Indian government's goal of promoting domestic manufacturing of solar PV [62,73] to become self-sufficient in the electricity supply [74] and in electricity access, will be extremely challenging.

In our analysis, the PV system grows every year until it can meet India's entire electricity demand by 2050, increasing from its initial size of 8 GW in 2016 (i.e., total installed capacity of PV in India) with zero storage under a different set of assumptions. This analysis adds to the existing body of knowledge in two primary ways. First, the heat and transport energy required to manufacture the PV system are excluded from the calculations; it was assumed that the meaningful electrification of the transport and industrial heat sectors will be unlikely to occur in the next few decades. Thus, renewable electricity will not substitute non-electricity-based energy. Therefore, we argue that separate energetic calculations for electricity, heat, and transport fuel are a more realistic metric for assessing the feasibility of renewable energy systems. Converting different types of energy into a single cumulative energy for net energy analysis may provide misleading insights.

Second, a dynamic analysis of the net electricity from a PV system was performed to show how the output changes as PV system grow to produce more and more electricity. Energetic analysis reveals more information in physical terms. The cannibalistic dynamics of net electricity from a large-scale, rapidly growing PV system shows the potential challenges. Contrary to several arguments raised in [32,47], this paper argued that lower net energy output would not be a problem; however, the rapid transition to PV system will require much higher quantities of all energy types (transport, heat, and electricity) than can be produced by the system itself during the period of rapid growth, thus becoming an energy-sink in the short term. Thus society faces the difficult choice of reallocating a large amount of electricity to a purpose that does not serve their needs immediately and will not for several years (depending on scenario). Politically coordinate such a decision is difficult. However, additional investment in fossil fuels will create carbon emissions.

5. Conclusion

The primary purpose of this paper was to investigate the energetic implications of transitioning toward a renewable electricity system running entirely on photovoltaic electricity system in India. The energetic flow model was developed to simulate inputs and outputs of electricity from PV system from 2016 to 2050. The results showed that building a PV system large enough to meet the nation's entire electricity demand by 2050 is possible; however, it will require substantial electricity investment from existing electricity supply, leading to a short-term electricity shortage. Thus, allocating such a significant amount of electricity in the present to support a low-carbon energy system that will only start providing society with surplus electricity in the future may be socially and politically challenging.

The short-term deficit can be reduced by increasing the electricity supply from fossil fuel-based generation or by reducing electricity demand, which would create trade-offs between carbon emissions and electricity access. Furthermore, India may also rely on imported PV panels and storage technologies, rather than manufacturing them domestically, to avoid the electricity shortfall; however, the burden of electricity security might shift from importing fossil fuels to importing PV panels. Thus, due to the intermittency and high embodied electricity of a PV system, achieving all three policy objectives (self-reliance in

electricity, climate mitigation and adequate electricity) for society by 2050 is going to be extremely challenging in most scenarios.

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